

# Iterative learning control: brief survey and categorization 1998 – 2004

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## Abstract

In this paper the iterative learning control (ILC) literature published between 1998 and 2004 is categorized and discussed, extending earlier reviews presented by two of the authors. The paper includes a general introduction to ILC and a technical description of the methodology. Selected results are reviewed and the ILC literature is categorized into subcategories within the broader division of application-focused and theory-focused results.

## Index Terms

Iterative learning control, literature review, categorization.

## I. INTRODUCTION

Iterative learning control (ILC) is an effective control tool for improving the transient response and tracking performance of uncertain dynamic systems that operate repetitively. Systems typically treated under the ILC framework are repetitively-operated dynamic systems, such as a robotic manipulator in a manufacturing environment or a chemical reactor in a batch processing application. The ILC notion can also be extended to include periodically-disturbed or periodically-driven dynamic systems, where the periodicity could be time-, state-, or trajectory-dependent. More generally, the key idea of ILC can be viewed as a multi-pass process. Historically, the first novel idea related to a multi-pass control strategy can be traced back to [116], published in 1974, though the stability analysis was restricted to classical control concepts and did not explicitly cover the ILC approach. It is

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widely accepted that the first ILC formulations were given by Uchiyama in [429], which was written in Japanese and published in 1978, and by Arimoto in [26], which was written by English and published in 1984. Interestingly, the essential idea of iterative learning was captured even before 1970, not in the archival literature, but in a U.S. patent, as explained in [65].

The purpose of this paper is to provide a summary and review of the recent trends in ILC research from both the application point of view and the theoretical point of view. We focus on the literature published between 1998 and 2004, logically extending three previous surveys presented by two of the authors (see [282], [275], [62]). Section I continues with a general introduction to ILC and a technical description of the methodology. In Section II we summarize the survey methodology we used and present selected results from the recent literature. Section III is the main part of the paper, where we separate the literature into application-focused results and theory-focused results, giving detailed sub-classifications of each of these broader categories. Section IV presents some concluding remarks.

#### *A. What is Iterative Learning Control?*

Control systems have played an increasingly important role in development and advancement of modern civilization and technology. Control problems arise in practically all engineering areas and have been studied both by engineers and by mathematicians. In industry, control systems are found in numerous applications, including quality control of manufactured systems, automation, network systems, machine tool control, space engineering, military, computer science, transportation systems, robotics, social systems, economic systems, and biological/medical engineering, among others. Mathematically, control engineering includes modelling, analysis, and design of control systems. The key feature of control engineering is the use of feedback signals for performance improvement of a controlled system. The branches of current control theories are broad and include classical control, robust control, adaptive control, optimal control, nonlinear control, neural network, fuzzy logic, and intelligent control.

Iterative Learning Control (ILC) is a relatively recent, but well-established, area of study in control theory. ILC, which can be categorized as an intelligent control methodology<sup>1</sup>, is an approach for improving the transient performance of systems that operate repetitively over a fixed time interval. Although control theory provides numerous design tools for improving the response of a dynamic system, it is not always possible to achieve desired performance requirements, due to the presence of un-modelled dynamics or parametric uncertainties that are exhibited during actual system operation or to the lack of suitable design techniques [274]. Thus, it is not easy to achieve perfect tracking using traditional control theories. ILC is a design tool that can be used to overcome the

<sup>1</sup>From “Defining Intelligent Control, Report of the Task Force on Intelligent Control,” IEEE Control Systems Society, Panos Antsaklis, Chair, December 1993: “... intelligent control uses conventional control methods to solve lower level control problems ... conventional control is included in the area of intelligent control. Intelligent control attempts to build upon and enhance the conventional control methodologies to solve new challenging control problems....”

shortcomings of traditional controller design, especially for obtaining a desired transient response, for the special case when the system of interest operates repetitively. For such systems, ILC can often be used to achieve perfect tracking, even when the model is uncertain or unknown and we have no information about the system structure and nonlinearity.

Various definitions of ILC have been given in the literature. Some of them are quoted here.

- The learning control concept stands for the repeatability of operating a given objective system and the possibility of improving the control input on the basis of previous actual operation data (Arimoto, Kawamura, and Miyazaki [27]).
- It is a recursive online control method that relies on less calculation and requires less *a priori* knowledge about the system dynamics. The idea is to apply a simple algorithm repetitively to an unknown plant, until perfect tracking is achieved (Bien and Huh [37]).
- Iterative learning control is an approach to improving the transient response performance of the system that operates repetitively over a fixed time interval (Moore [274]).
- Iterative learning control considers systems that repetitively perform the same task with a view to sequentially improving accuracy (Amann, Owens, and Rogers [9]).
- ILC is to utilize the system repetitions as experience to improve the system control performance even under incomplete knowledge of the system to be controlled (Chen and Wen [60]).
- The controller that learns to produce zero tracking error during repetitions of a command, or learns to eliminate the effects of a repeating disturbance on a control system output (Phan, Longman, and Moore [332]).
- The main idea behind ILC is to iteratively find an input sequence such that the output of the system is as close as possible to a desired output. Although ILC is directly associated with control, it is important to note that the end result is that the system has been inverted (Markusson [266]).
- We learned that ILC is about enhancing a system's performance by means of repetition, but we did not learn how it is done. This brings us to the core activity in ILC research, which is the construction and subsequent analysis of algorithms (Verwoerd [434]).

All definitions about ILC have their own emphases. However, a common emphasis of these definitions is the idea of "repetition." Learning through a *predetermined* hardware repetition is the key idea of ILC. Hardware repetition is a physical layer on the uniformly distributed time axis for providing experience to the mental layer of ILC. "Predetermined" means that the ILC system requires some postulates that define the learning environment of a control algorithm. A person learns his/her living environment by experience where the physical layer is their daily activity and the mental layer is the memory of strongly-perceived events that are closely related to his/her interest. These strongly-perceived events of the past provide knowledge to a human being that can be used for their current

activity. In ILC, the current activity is a control force and the past experience is stored as data. A difference between human learning and machinery learning is in the “predetermined” aspect. For a human being, knowledge by learning could be based on similarity and impression, whereas in a machine, the initial setup, fixed time point, uniform sampling, repetitive desired trajectory, etc. are predetermined, which may be used to determine the future actions of the hardware machine.

Following the definitions quoted above, we can say that ILC is an approach to improve the transient response performance of an unknown/uncertain hardware system that operates repetitively over a fixed time interval by using the previous actual operation data to compensate for uncertainty. The key question of ILC is how to eliminate the uncertainty by using past performance information on the current trial. If the system uncertainty and external disturbances are predetermined on the uniformly-distributed-repetitive time axis, then finding an “inverse” of these predetermined effects can be thought of as the main objective of ILC.

### B. Technical Overview of Iterative Learning Control

In this section we summarize basic ILC algorithms, both continuous-time and discrete-time, and their convergence properties. For discrete-time ILC we focus especially on the so-called supervector framework.

1) *Continuous-time ILC*: As shown from the categorization below in Section III, the scope of ILC research is so wide that it is nearly impossible to introduce all branches of ILC. In this subsection, the basic ideas of ILC algorithms are briefly reviewed. Let us consider the following linear continuous-time system:

$$\dot{x}_k(t) = Ax_k(t) + Bu_k(t) \tag{1}$$

$$y_k(t) = Cx_k(t) \tag{2}$$

The control task is to servo the output  $y_k$  to track the desired output  $y_d$  on a fixed interval  $t \in [0, T]$  as the iteration  $k$  increases. In classical ILC, the following basic postulates are required, although in recent ILC research some of these postulations have been relaxed:

- Every trial (pass, cycle, batch, iteration, repetition) ends in a fixed time of duration.
- Repetition of the initial setting is satisfied. That is, the initial state  $x_k(0)$  of the objective system can be set to the same point at the beginning of each iteration.
- Invariance of the system dynamics is ensured throughout the repetition.
- Output  $y_k(t)$  is measured in a deterministic way.
- The system dynamics are deterministic.

Under these assumptions, if the system has relative degree one or less, an iterative learning control scheme of the “Arimoto-type” [25], [26], given by:

$$u_{k+1} = u_k + \Gamma \dot{e}_k, \quad (3)$$

where  $e_k(t) = y_d(t) - y_k(t)$  and  $\Gamma$  is a diagonal learning gain matrix, ensures

$$\lim_{k \rightarrow \infty} y_k(t) \rightarrow y_d(t)$$

for all  $t \in [0, T]$  if

$$\|I - CB\Gamma\|_i < 1, \quad (4)$$

where  $\|\cdot\|_i$  is an operator norm and  $i \in \{1, 2, \dots, \infty\}$ . Notice that the basic formula for selecting the learning gain given in (4) does not require information about the system matrix  $A$ , which implies that ILC can be effective for model-uncertain systems (though some knowledge of the system structure, such as its relative degree, is needed). This is a key characteristic of ILC.

Starting from the classical Arimoto-type ILC algorithm we can develop a number of more general expressions. For instance, a “PID-like” update law can be given as [274]:

$$u_{k+1} = u_k + \Phi e_k + \Gamma \dot{e}_k + \Psi \int e_k dt \quad (5)$$

where  $\Phi$ ,  $\Gamma$ , and  $\Psi$  are learning gain matrices. A higher-order ILC (HOILC - meaning information from more than one previous trial is used in the ILC algorithm) PID-like update rule [60] can be formulated as:

$$u_{k+1} = \sum_{k=1}^N (I - \Lambda) P_k u_k + \Lambda u_o + \sum_{k=1}^N \left( \Phi_k e_{i-k+1} + \Gamma_k \dot{e}_{i-k+1} + \Psi_k \int e_{i-k+1} dt \right). \quad (6)$$

If  $\sum_{k=1}^N P_k = I$ , then by properly choosing the learning gain matrices we can ensure that  $e_k$  converges to zero asymptotically [60]. Similarly, a time-varying, P-type (meaning no derivative and integral effects) version of the ILC update rule given in (5) can be written as:

$$u_{k+1}(t) = u_k(t) + \Gamma_k(t)(y_d(t) - y_k(t)) \quad (7)$$

where  $\Gamma_k(t)$  is the proportional learning gain matrix that is now time-varying. In this first-order ILC algorithm, by properly choosing the learning gain matrix  $\Gamma_k(t)$ , the ILC process will converge to zero steady-state error for systems of relative degree zero. Similar results can be developed for systems of relative degree one or higher. In this simple ILC algorithm, the key feature of ILC is to make use of information from the most recent past trial for

the current update. Thus, it is also natural to derive time-varying HOILC update rules such as

$$u_{k+1}(t) = u_k(t) + \sum_{i=k}^{i=k-l} \Gamma_i(t)(y_d(t) - y_i(t)) \quad (8)$$

or

$$u_{k+1}(t) = \sum_{i=k}^{i=k-l} \Lambda_i(t)u_i(t) + \sum_{i=k}^{i=k-l} \Gamma_i(t)(y_d(t) - y_i(t)), \quad (9)$$

which uses not only the most recent previous control input/transient error information, but all of the previous control inputs/transient error information. These algorithms highlight the perspective that ILC is “a control law that uses all available past information for the performance improvement of a periodic system.” This idea is depicted in block diagram form in Fig. 1, which shows the next trial’s control input to be calculated from the previous trial’s control input and transient error. In this figure, including more than one previous trial is accomplished by incorporating trial-to-trial dynamics (e.g., memory) in the block labeled “Iterative Learning Controller.”

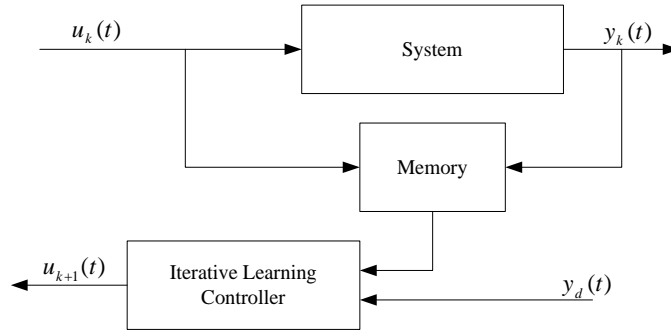


Fig. 1. Basic ILC configuration.

2) *Discrete-time ILC*: So far, we have considered continuous-time ILC algorithms. However, since microprocessor-based systems are widely used in actual applications, it is practically desirable to use a discrete-time or sampled-data formulation. To this end, consider the discrete-time state-space model given as follows:

$$x_k(t+1) = Ax_k(t) + Bu_k(t) \quad (10)$$

$$y_k(t) = Cx_k(t). \quad (11)$$

We suppose the system operates on a finite-horizon given by  $t \in [0, N]$  where  $t$  is an integer and that the system has relative degree  $m$ . Thus, each iteration domain consists of a finite number of discrete time points, which can be used via lifting to form the following so-called “supervectors:”

$$U_k = (u_k(0), u_k(1), \dots, u_k(N-1)) \quad (12)$$

$$Y_k = (y_k(m), y_k(m+1), \dots, y_k(N-1+m)) \quad (13)$$

$$Y_d = (y_d(m), y_d(m+1), \dots, y_d(N-1+m)) \quad (14)$$

$$E_k = Y_d - Y_k = (E_k(m), E_k(m+1), \dots, E_k(N-1+m)) \quad (15)$$

With these definitions, the linear plant can be described by  $Y_k = HU_k$ , where  $H$  is a matrix of rank  $N$  whose elements are Markov parameters of the plant  $G(z)$ :

$$H = \begin{bmatrix} h_m & 0 & 0 & \dots & 0 \\ h_{m+1} & h_m & 0 & \dots & 0 \\ h_{m+2} & h_{m+1} & h_m & \dots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ h_{m+N-1} & h_{m+N-2} & h_{m+N-3} & \dots & h_m \end{bmatrix} \quad (16)$$

In the literature, the supervector framework has been generalized to systems given by:

$$x_k(t+1) = (A + \Delta A)(t)x_k(t) + (B + \Delta B)(t)u_k(t) + v(k, t) \quad (17)$$

$$y_k(t) = (C + \Delta C)(t)x_k(t) + w(k, t), \quad (18)$$

where now  $A, B$ , and  $C$  are time-varying and  $\Delta A, \Delta B$ , and  $\Delta C$  are model uncertainties, also time-varying, but possibly characterized in the frequency domain or via interval mathematics, and  $v(k, t)$  and  $w(k, t)$  are time and iteration-dependent process and measurement noises, respectively. In this case, by defining suitable supervectors representing the noise and disturbance signals, the system can be represented by

$$Y_k = (H + \Delta H)U_k + D_k \quad (19)$$

where the ‘‘plant’’  $H$  is still lower-triangular but no-longer Toeplitz,  $D_k$  represents the collective effects of  $v(k, t)$  and  $w(k, t)$ , and  $\Delta H$  captures the uncertainty in the plant. Finally we note that even more generally, for discrete-time multipass processes we may allow the plant and the plant uncertainty to vary from trial-to-trial, resulting in a lifted model given by:

$$Y_k = (H_k + \Delta H_k)U_k + D_k \quad (20)$$

As discussed in [276], this formulation effectively transforms a two-dimensional problem into a multivariable one-dimensional problem.

Now consider the update algorithm in the supervector framework. A typical ILC update scheme for a plant with relative degree one, such as:

$$u_{k+1}(t) = u_k(t) + \Gamma(q)e_k(t+1) \quad (21)$$

where  $\Gamma(q)$  denotes a linear time-invariant filter using the standard abuse of notation, would be expressed in the supervector notation as

$$U_{k+1} = U_k + LE_k. \quad (22)$$

The learning gain matrix  $L$  could be fully populated in the general case, corresponding to a time-variant, non-causal learning operator or could have various forms of structure imposed, such as lower- or upper-triangular Toeplitz, in the cases of completely causal or completely non-causal learning operators, respectively, or band-diagonal, corresponding to FIR averaging operators (causal and non-causal), etc.

We may further consider higher-order ILC (HOILC) in the supervector framework. Suppose our discrete plant has transfer function  $G(z) = C(zI - A)^{-1}B$ . It is assumed that  $t \in [0, N]$ . Without loss of generality, we take  $m = 1$  and  $CB \neq 0$ . An early version of the following HOILC update rule was first introduced in [276]:

$$\begin{aligned} U_{k+1} = & -D_n U_k - D_{n-1} U_{k-1} - \cdots - D_0 U_{k-n} \\ & + N_{n+1} E_{k+1} + N_n E_k + \cdots + N_1 E_{k-n+1} + N_0 E_{k-n}, \end{aligned} \quad (23)$$

where  $k$  denotes the iteration trial;  $D_i$  are fixed learning gain matrices associated with the previous control input vectors;  $N_i$  are fixed learning gain matrices associated with the previous error vectors; and  $n$  is the number of the past trials used for the current control update (if  $n = 0$  we have first-order ILC and if  $n \geq 1$  we have higher-order ILC). This update equation expands on the results of [276] by the inclusion of the term  $N_{n+1} E_{k+1}$ . In the literature this term is called ‘‘current cycle feedback’’ (also called ‘‘current iteration feedback’’ or CITE) and accounts for the action of a typical feedback controller that would be used even in the absence of ILC. Note that from the perspective of a design problem, the CITE gain  $N_{n+1}$  must be causal (i.e., lower-triangular), while all the other matrices in (23) may be fully-populated as they act on information from the past.

3) *ILC Convergence*: Whether considering continuous-time or discrete-time ILC, a key focus in ILC literature has been the design of the ILC update algorithm and then the subsequent analysis of the convergence properties of the algorithm. Because the time-axis in an ILC problem is finite, ILC convergence refers to stability along the iteration axis. There are two convergence concepts to consider: asymptotic stability (AS) and monotonic convergence (MC). The former is concerned with whether an ILC algorithm converges as the number of iterations goes to infinity. The latter is concerned with the error getting smaller-and-smaller (in the sense of some norm) from iteration-to-iteration.

To illustrate the difference between AS and MC for first-order discrete-time ILC, consider the Arimoto-type update (22) where  $L = \text{diag}(\gamma)$ . If the system is characterized by the matrix  $H$  and the first Markov parameters is  $h_1$ , then the (necessary and sufficient) condition for AS is  $|1 - \gamma h_1| < 1$ , whereas the (sufficient) condition for MC is  $\|I - HL\|_i < 1$ , a stronger condition to achieve, but one that ensures that the error gets smaller on each trial.

To discuss convergence for HOILC it is helpful to introduce a shift operator,  $w$ , with the property that

$$w^{-1}u_k(t) = u_{k-1}(t).$$

This is just the standard  $z$ -transform, re-named to reflect the fact that it is operating from trial-to-trial, with time  $t$  fixed, as opposed to the standard  $z$ -transform operator, which operates from time step-to-time step, with  $k$  fixed. Thus, we may write  $Y_k = HU_k$  as  $Y_k(w) = HU_k(w)$ . This represents the nominal plant. With this notation, taking the  $w$ -transform of both sides of the HOILC equation (23) with  $N_{n+1} = 0$  (i.e., no CITE) and combining terms gives

$$D_c(w)U(w) = N_c(w)E(w)$$

where

$$\begin{aligned} D_c(w) &= Iw^{n+1} + D_nw^n + \dots + D_1w + D_0 \\ N_c(w) &= N_nw^n + N_{n-1}w^{n-1} + \dots + N_1w + N_0 \end{aligned}$$

which can also be written in a matrix fraction as  $U(w) = C(w)E(w)$  where

$$C(w) = D_c^{-1}(w)N_c(w)$$

Combining this controller representation with the plant, the repetition-domain closed-loop dynamics become:

$$G_{cl}(w) = H[D_c(w) + N_c(w)H]^{-1}N_c(w)$$

Thus we can say that the system is AS if  $G_{cl}$  is stable. Standard techniques from linear MIMO controller design can be used to design the learning matrices in (23) to ensure AS. However, the study of MC is still an open question for HOILC.

## II. FROM 1998 TO 2004: OVERVIEW

### A. Methodology of Literature Search

There have been a number of previous reviews and surveys of ILC. Of particular note is the two part ILC overview and critical analysis papers [455], [456] by Xu, which includes references through 2002. Part I [455] gives a thorough analysis of contraction mapping-based ILC while Part II [456] describes the use of energy functions for ILC and relates ILC to adaptive control. In previous publications, two of the authors of the present paper have presented major ILC surveys in 1992 (Section 2 of [282]), 1997 (Chapter 1 of [62]), and 1999 (Chapter 4.4 of [275]). Section 2 of [282] provided detailed explanations about ILC research before 1990. The first part of Section 2

of [282] introduced Japanese researchers who suggested LTI Arimoto-type gains (see below), PID-type gains, and gradient method-based optimization algorithms for ILC. In the latter part of Section 2 of [282], literature dealing with nonlinear ILC, robustness of ILC, adaptive schemes in ILC, the optimal control approach to ILC, and neural network-based ILC was introduced. An early classification of ILC works was given in Chapter 1 of [62] and a wider ILC classification was given in Chapter 4.4 of [275]. Note that in [275] the literature published before 1997 was classified into two main categories: theoretical works and applications. We have retained this approach in this paper. Note that a total number of 256 publications were covered in [275], which were obtained by searching on the keywords (“Control” AND “Learning” AND “Iterative”). Also, though it is out of the time range of the present survey, we note a recent survey that appeared in 2006, which provides a detailed technical survey on ILC algorithms along with new results on the design of the so-called Q-filter [42].

The present survey began with a search on the “Web of Science<sup>2</sup>” and “IEEE Xplore<sup>3</sup>” sites conducted on January 4, 2005. Table I shows the search results. As shown in this table, from the keywords (“Control” AND “Learning” AND “Iterative”), we have a total number of 877 publications. Given that there were 256 citations in [275], we can argue that since 1998 there have been approximately 600 publications related to ILC. A more broad, but reliable broader search was also carried out using the keyword combinations (“Iterative” AND “Learning”) and (“Learning” AND “Control”), from which we have 1910 and 20260 publications, respectively. Thus, connected to the word “Learning,” a great deal of literature has been published. We also searched under a related topic using the keywords “Repetitive Control,” from which we obtained 309 publications. Given these large number of publications, in this paper our review is restricted to the literature obtained by searching under the exact phrase “Iterative Learning Control,” from which 510 different publications were found. However, for a reliable survey, we also decided to include papers from selected conferences and journals that could not be searched in the Web of Science and IEEE Xplore databases. Specifically, we also considered papers in the 1999 and 2002 World Congresses (WC) of the International Federation of Automatic Control (IFAC), the 2000 and 2002 Asian Control Conferences (ASCC), the 2001 European Control Conference (ECC), the 7<sup>th</sup> Mechatronics Conference, the *Asian Journal of Control* (AJC), and several other miscellaneous conferences where ILC papers appeared (see Table II). Thus, this paper covers IEEE conference and journal papers, international (SCIE) journal papers, IFAC conference papers, and Asian control conference papers.

Fig. 2 gives a graphical depiction of the number of ILC publications since 1990 in international conference proceedings and journals. As shown in this figure, the number of publications increased steadily up to 2002, but then seems to have tapered off. We do not have an explanation for this effect, though the large number of conference publications in 2002 may be due to the IFAC WC. It is also interesting to note Table III, which shows the regional

<sup>2</sup><http://isi01.isiknowledge.com/portal.cgi/wos>

<sup>3</sup><http://ieeexplore.ieee.org>

distribution of the authors of the literature which was published in IEEE conference proceedings and SCIE journals (from the Web of Science database).

Tables I and II and Fig. 2 give gross statistics about the number of ILC publications. In the next subsection and in Section III we expand on these tables by reviewing selected results from the recent literature and then separating the papers into detailed sub-classifications, respectively.

TABLE I  
ILC RELATED PUBLICATIONS FROM WEB OF SCIENCE AND IEEE XPLORE.

Search options	From “Web of Science”	From “IEEE Conference”	Total
Iterative + Learning	793	1117	1910
Learning + Control	12739	7521	20260
Iterative + Learning + Control	367	510	877
Iterative Learning Control	241	269	510
Repetitive Control	150	159	309

TABLE II  
MISCELLANEOUS ILC-RELATED PUBLICATIONS FROM 1998 TO 2004.

IFAC 1999 WC	IFAC 2002 WC	2000 ASCC	2002 ASCC	AJC	Others	Total
12	19	20	11	14	7	83

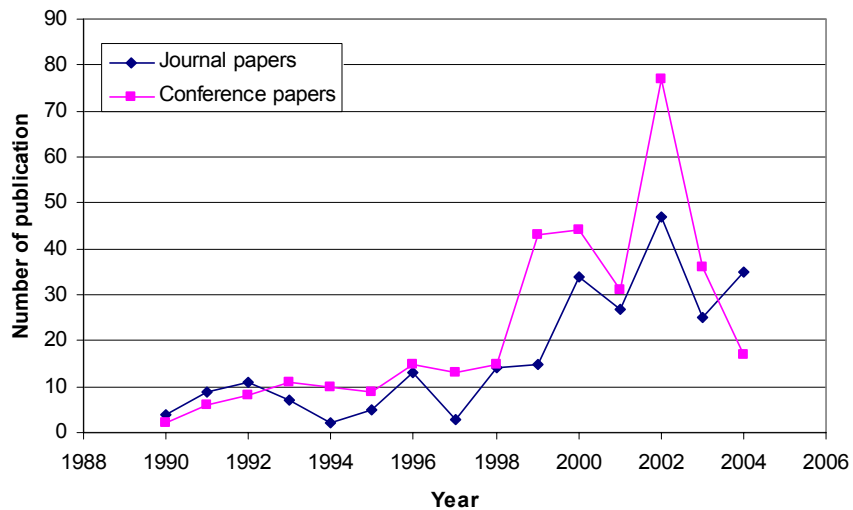


Fig. 2. Number of ILC related-publications in conference proceedings and journals.

### B. From 1998 to 2004: Brief Comments on Selected Literature

The first ILC monograph [274] was published in 1993. After 1998, there were an editorial publication [38] in 1998; three special issues (a special issue of the *International Journal of Control* [285] in 2000), (a special issue

TABLE III  
REGION DISTRIBUTION OF AUTHORS OF IEEE CONFERENCE PAPERS AND SCI JOURNAL PAPERS.

Region	From “Web of Science”	From “IEEE Conference”	Total
China	18	55	73
Korea	60	15	75
Singapore	68	39	107
Japan	32	30	62
Taiwan	9	5	14
UK	47	29	76
Europe	42	30	72
USA	63	39	99
Canada	11	8	19
Other areas	6	6	12

of the *Asian Journal of Control* in 2002), and (a special issue of the *Intelligent Automation and Soft Computing: Learning and Repetitive control* [115]); and two more ILC monographs [60], [481] in 1999 and in 2003 respectively. [38] is the outcome of the 2nd Asian control conference held in Seoul in July, 1997 and [285] is the outcome of the 1998 IEEE conference on Decision and Control held in Tampa, Florida, USA. It is useful to read Chapter 1 and Chapter 2 of [38]. In Chapter 1, as a conclusion, Arimoto argued that the P-type update rule may be more natural than D-type ILC. In Chapter 2, Xu and Bien described several key issues in ILC research and commented on the limitations of ILC applications. Their discussions were given in three different categories: tasks, a connectivity of ILC to other control theories, and ILC issues in a future research direction. In [60], the nonlinear higher-order ILC was developed to address robust ILC stability and in [481], nonlinear ILC, mostly based on the idea of a composite-energy function, was described.

We also note that since 1998 at least 18 different Ph.D dissertations can be found, as shown in Table IV, which was developed from a search on the “Digital Dissertations” web-site<sup>4</sup> combined with information suggested by an anonymous reviewer [176], [304], [447], [385], [336], [246], [254], [434], [103], [500], [200], [152], [131], [514], [266], [503], [306], [261].

In the following subsections we will briefly review the special issue, Vol 73, No 10, of the *International Journal of Control* (IJC) [285] and the Ph.D dissertations. The IJC special issue includes well-refined ILC topics while the Ph.D dissertations represent interesting ILC applications and some important theoretical developments.

1) *IJC Special Issue, Vol 73, No 10, 2000*: The IJC special issue contained fifteen articles that were based on presentations made at the *Iterative Learning Control Workshop and Roundtable*, a two-day meeting of twenty-eight ILC researchers preceding the 1998 IEEE Conference on Decision and Control. Papers in the special issue included

<sup>4</sup><http://wwwlib.umi.com/dissertations/gateway>

TABLE IV  
ILC-RELATED PH. D DISSERTATIONS.

	1998	1999	2000	2001	2002	2003	2004	Total
Number	1	1	3	2	3	0	8	18

theoretical contributions related to the authors' expertise in conventional control theories as well as applications ranging from semiconductors to robots to process control.

In [28], Arimoto presented ideas on the equivalence between “learnability”, “output-dissipativity”, and “strictly positive realness”. Based on theorems 1-4 of [28], it is possible to check if there exists an ILC controller to give input-output  $l_2$  stability of the controlled-system. In the general case when  $D = 0$ , learnability can be checked by investigating if there exist two positive-definite symmetric matrices  $X$  and  $Q$  such that

$$A^T X + X A = -Q, \quad X B = C^T. \quad (24)$$

In [130], a linear quadratic ILC scheme was modified so as to reduce the dimension of the supervectors in calculating an optimal control at each trial and to estimate an unknown system model based on conjugate basis vectors. French and Rogers [126] provided an adaptive ILC with a calculated cost for  $l_p$ -bounded disturbances. This paper also discussed how to handle the robustness issue in the adaptive control framework. Owens and Munde [312] also provided a new adaptive approach for ILC systems. They included the current error feedback into an adaptive control law to exploit the fact that the most recent error data reflects the current performance most closely. Also, by including the feedback signal, they could stabilize an unstable plant during each trial. Xu, et al., suggested a robust learning controller (RLC) in [485] for robotic manipulators to compensate for state-independent periodic uncertainties and to suppress non-periodic system uncertainties. As commented in the same paper, the results of [485] can be applied to various periodically-disturbed systems and to uncertain dynamic systems (see Section III-B.8). In [326], the initial state error problem was handled. In [187], Hillenbrand and Pandit provided a design scheme for 2-norm convergence using the idea of reduced sampling rate. Anticipatory ILC was suggested by Wang at the ILC Round Table Workshop held at the 1998 IEEE CDC and published in [438], [439], whereby an ILC update rule is given by:

$$u_{i+1}(t) = u_i(t) + L(\cdot)[y_d(t + \Delta) - y_i(t + \Delta)] \quad (25)$$

with a saturation condition also included on the input. Notice that the update rule is different from D-type or P-type (also compare this with [8]). In [79], Chien suggested an ILC design method based on fuzzy control for sampled-data systems. In [357], a state observer and a disturbance model were used to the learning controller. Longman gave a valuable discussion in [259], providing several important guidelines for the actual design of ILC

and repetitive control (RC) algorithms. Longman also provided experimental test results and detailed explanations on the practical uses of ILC. In [283], Moore proved a convergence analysis for ILC systems with a desired periodic output trajectory. The final three papers of the special issue were dedicated to ILC applications: [356] used an  $H_\infty$  approach for a wafer positioning control problem, [308] applied ILC to non-holonomic systems, and [35] showed how ILC can be utilized for position control of chain conveyer systems.

2) *ILC-related Ph.D Dissertations Since 1998*: First of all, note that our search for Ph. D dissertations published since 1998 is very limited, because “Digital Dissertations” does not include all the schools in the world and we were not able to personally be aware of all the dissertations published everywhere on this topic. Nonetheless, we tried to include all the Ph.D dissertations of which we were aware. In 2004, the number of Ph.D dissertations in ILC significantly increased as shown in Table IV. In [176], Hätönen studied the algebraic properties of a standard ILC structure and made progress in the norm-optimal ILC field. Verwoerd [434] suggested equivalent feedback controllers for causal ILC and non-causal ILC based on an admissibility concept. Note that a similar discussion to [434] can be found in [155], [314], [156]. Dijkstra [103] showed some exciting ILC applications. In his dissertation, lower-order ILC has been applied to the different wafer-stages. In addition, for finite-time ILC, Dijkstra provided several interesting theoretical developments in Chapter 4 of [103]. In [306] Oh introduced a local learning concept to avoid undesirable overshoot during the transient. Norrlöf [304] presented a number of useful results on the theory of ILC, including ideas about the use of models in ILC and presentation of a successful ILC application for a robotic manipulator. Markusson [266] used ILC to find an inversion of the system, particularly focused on noncausal and nonminimum systems. A time-frequency adaptive Q-filter ILC was suggested for nonsmooth-nonlinearity compensation by Zheng in [514] and the idea was used for an injection molding machine. ILC and RC were summarized and some new results for nonlinear, nonminimum phase systems were developed by Ghosh in [152]. In [500], Yang studied ILC based on neural networks and in [131], Frueh suggested the basis-function-model-reference adaptive learning controller (see also [130]). The suggested method in [131] has several advantages. One in particular is an adaptive property to account for slowly-varying plant parameters or errors from the initial model. Huang [200] introduced Fourier series-based ILC algorithms for the tracking performance improvement. In [447], several important issues arose from the field of learning and repetitive control were addressed; for example, indirect adaptive control ideas applied to learning control were introduced and based-functions were used to show that the learning control and the repetitive control problems are mathematically the same under the some conditions. Songchon showed, in [385], that learning control has the ability to bypass the waterbed effect, which is a fundamental problem in traditional feedback controls. In [246], LeVoci developed methods for predicting the final error levels of general first order ILC, of higher order ILC including current cycle learning, and of general RC, in the presence of noise, using frequency response methods. Three main difficulties in the area of linear discrete-time ILC were

addressed in [254]: (i) The number of output variables for which zero tracking error can be achieved is limited by the number of input variables; (ii) every variable for which zero tracking error is sought must be a measured variable; and (iii) in a digital environment, the inter-sample behavior may have undesirable error from ripple. An interesting application of optimal ILC was utilized for a chemical molding process in [503]; Ma [261] showed that an ILC algorithm can be used for the vision-based tracking systems; and in [336], Phetkong used ILC on a cam designed and built using a 2-3 polynomial profile and it was shown that eight cycles for learning were seen to be sufficient to effectively accomplish the morphing of the cam behavior.

### III. FROM 1998 TO 2004: CATEGORIZATION

In this section, we separate the literature into two different parts. The first part is related to the literature that focuses on ILC applications and the second part is related to the literature focused on theoretical developments. Of course, it is often difficult to separate the literature into these two groups, so the categorizations given in this section are largely based on authors' subjective opinions. Also, note that in this section we do not make detailed comments, but simply categorize the papers.

#### A. Literature Related to ILC Applications

In [275], ILC literature dealing with applications was categorized as: "robotics" and "applications." In "robotics," detailed categories were given as "elastic joints," "flexible links," "cartesian coordinates," "neural networks," "cooperating manipulators," "hybrid control," and "nonholonomic." In applications, detailed categories were given as "vehicles," "chemical processing," "mechanical/manufacturing systems," "nuclear reactor," "robotics demonstrations," and "miscellaneous." In this paper, we began by trying to follow the above categories, but found it difficult to restrict all the publications between 1998 and 2004 into the categories given above (see Table 4.2 of [275]). Thus, we make more detailed categories, including as "Robots," "Rotary systems," "Batch/factory/chemical processes," "Bio/artificial muscle," "Actuators," "Semiconductors," "Power electronics" and "Miscellaneous," and in each category, we provide further sub-categories.

1) *Robots*: As shown in [275], robotics is the most active area of ILC application. Since 1998, this continues to be the case. Robotic applications of ILC have included:

- General robotic applications, including rigid manipulators and flexible manipulators [158], [418], [379], [167], [301], [210], [389], [417], [19], [211], [34], [204], [495], [193], [506], [505], [166], [515], [252], [213], [292], [194], [224], [93], [504], [219].
- Mechatronics design [430], [449].
- Robot applications with the adaptive learning [390].
- With Kalman filter [295].

- Impedance matching in robotics [289], [437], [44], [30].
- Table tennis [268].
- Underwater robots [373], [374], [220], [372].
- Acrobat robots [497], [445].
- Cutting robots [212].
- Mobile robots [279], [67].
- Gantry robots [173], [352].
- Arc Welding process [191].
- Micro-scale robotic deposition [41].

2) *Rotary Systems*: Rotational motion is generally disturbed by position-dependent or time-periodic external disturbances. Thus, control of rotary systems is a good candidate for ILC application. Papers related to this area include:

- The vibration suppression of rotating machinery [249].
- Switched reluctance motors (SRM) [371], [369], [367], [368], [370].
- Permanent-magnet synchronous motor (PMSM) [232], [462], [342], [243], [344], [231], [461], [343].
- Linear motors [408].
- (Ultrasonic) induction motor [366], [264], [263].
- AC servo motor [378].
- Electrostrictive servo motor [196].

3) *Batch/Factory/Chemical Process*: The number of ILC applications in process control has increased significantly since 1998. The literature includes:

- Tracking control of product quality in agile batch manufacturing processes [453], [238].
- Chemical reactor [271], [270], [247], [507], [87].
- Water heating system [459].
- Laser cutting [428].
- Chemical process [145], [457], [40], [183], [413].
- Batch process [454], [458], [85], [415].
- Industrial extruder plant [320], [321], [322], [319].
- Moving problem of liquid container [163], [353], [162].
- Packaging and assembly [39].
- Injection molding [72], [411].

4) *Bio/Artificial Muscle*: Bio-engineering or bio-medical applications are not yet a popular ILC application area, but slowly the number of applications is increasing, as evidenced by the following:

- Bio-medical applications such as dental implants [202], [203].
- Functional neuro-muscular stimulation (FNS) application [107], [451].
- Human operator [12].
- Artificial muscle [195].
- Pneumatic system [46].
- Smart microwave tube [1], [375].
- Biomaterial applications [436].

5) *Actuators*: ILC applications to non-robotic/non-motor actuators are closely related to the mechanical hard-nonlinearity compensation problem discussed in Section III-B.8:

- A proportional-valve-controlled hydraulic cylinder system [45].
- Electromechanical valve [189], [331], [190].
- The Hysteresis problem of a piezoelectric actuator [260].
- Linear actuators [242], [412].

6) *Semiconductor*: It is quite interesting to see that ILC is widely applied in the semiconductor production process. Between 2001 and 2003, the following literature was published in semiconductor applications: [499], [237], [92], [102], [86], [101], [84], [358], [100], [99]. For a more detailed discussion of the application of ILC to semiconductor manufacturing processes, refer to [103].

7) *Power Electronics*: Examples of ILC applications to electrical power systems can be found in the following:

- Electronic/industrial power systems [512], [511], [513], [442].
- Inverters [36], [2].

8) *Miscellaneous*: Many miscellaneous applications of ILC are described in the following papers:

- Traffic [192].
- Magnetic bearing [98], [73].
- Aerospace [61], [69].
- Linear accelerator [230].
- Dynamic load simulator [441].
- Hard disk drive [475], [476].
- Temperature uniformity control [236], [269], [240].
- Visual tracking [251].
- Quantum mechanical system [333].

- Piezoelectric tube scanner [188].

Fig. 3 plots the number of papers focused on the use of ILC in applications. As shown in this figure, ILC has most-dominantly been applied to the area of robotics. However, notably, ILC has also been widely used in rotational motion control systems, in the process control industry, and for semiconductor manufacturing processes.

We also note that to check the practical uses of ILC, we searched United States patent abstracts using the keywords “Iterative” AND “Learning.”<sup>5</sup> From this search, we found ILC-related patents in motor control [341], process control [160], disk drive control [68], and network communication [218].

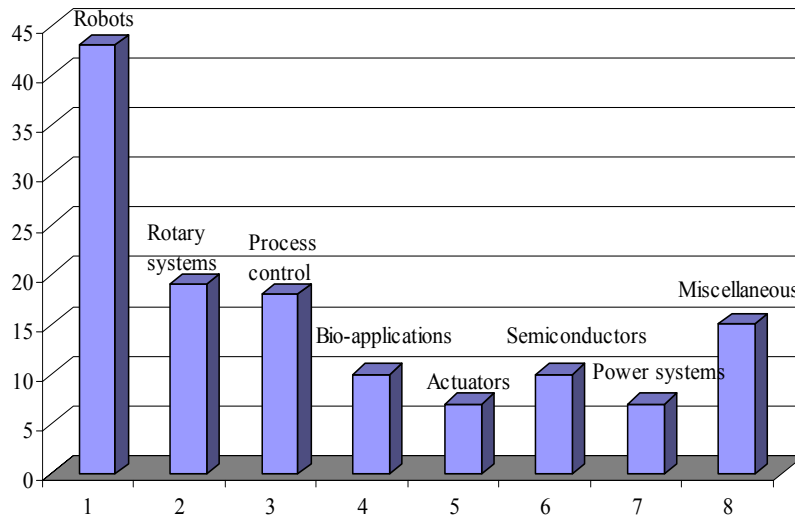


Fig. 3. Publication number of application-focused ILC literature.

### B. Literature Related to ILC Theories

Since the spectrum of the theoretical developments is so broad and individual papers often treat several different topics, assigning a given paper to a specific category can be quite subjective. Our approach was to try to separate papers that considered ILC as a specific topic from those that connected ILC analysis with other control theory topics. Our general categories were defined as “General (Structure),” “General (Update Rules),” “Typical ILC Problems,” “Robustness,” “Optimal and Optimization,” “Adaptive,” “Fuzzy and Neural,” “Mechanical Nonlinearity Compensation,” “ILC for Other Repetitive Systems and Control Schemes,” and “Miscellaneous.” The first three categories are related to unique ILC problems (i.e., ILC’s own issues not related to other control theories). The next four categories (robust, optimal, adaptive, fuzzy/neural) are for papers that combine or use results from these specific fields to advance the theoretical developments of ILC. The next two categories consider special cases where ILC has been applied to develop theoretical solutions to these special problem classes (mechanical nonlinearity, repetitive control) and the final category collects miscellaneous contributions.

<sup>5</sup><http://patft.uspto.gov/netahtml/search-bool.html>

1) *General (Structure)*: In this category, we include literature related to “ILC structure,” “convergence analysis,” “stability analysis,” and “basic theoretical works.” In [316], Owens studied an ILC algorithm using the following update rule:

$$u_{k+1}(t) = \alpha u_k(t) + K e_{k+1}(t) \quad (26)$$

which leads to the steady-state error expression  $e_\infty = (I + GK_{eff})^{-1}y_d$ , where  $G$  is a plant,  $y_d$  is the desired trajectory, and  $K_{eff} = K/(1 - \alpha)$ . Relationships were given between the steady-state error, the learning gains, and the structure of the ILC system. In [155], [314], [156], the equivalence of current cycle (single iteration) feedback control and ILC was discussed. Goldsmith showed that a learning controller updated by  $u_k = Fu_{k-1} + Ce_k + De_{k-1}$  is equivalent to a feedback controller  $u(t) = Ke(t - 1)$  if  $K$  is determined by  $K = (I - F)^{-1}(C + D)$ . This result is intuitively true and implies that the iterative learning controller is also eventually a feedback controller, based on the fact that ILC is a controller for finding the best feedforward gain in the time domain and the best feedback controller in the iteration domain. In [29], Arimoto and Naniwa used a positive real condition on the plant for defining passivity and output-dissipativity of LTI ILC systems. ILC convergence was then proved based on the strictly proper and positive realness of the plant in theorem 1 of [29], and uniform convergence was proved in theorem 2 of [29]. Eventually, this convergence can be interpreted as learnability, which is defined as the existence of a function norm  $\|\cdot\|$  such that  $\|y_d - y_k\| \rightarrow 0$  as  $k \rightarrow \infty$ . In [172], Hätönen, Feng, and Owens showed that if a plant  $G$  is positive (i.e.,  $\exists \sigma > 0$  such that  $u^T G u \geq \sigma u^T u$  for any  $u \neq 0$ ), then for the ILC system updated by  $u_{k+1}(t) = u_k(t) + \gamma_{k+1} e_k(t + 1)$  with learning gain  $\gamma_{k+1} = \frac{e_k^T G e_k}{w + e_k^T G^T G e_k}$ , the resulting error sequence satisfies  $e_k \rightarrow 0$  as  $k \rightarrow \infty$ . In [256], Longman and Huang discussed the large overshoots in the transient response that can occur in ILC even when the system is asymptotically convergent. They noted that the trajectory error of the first iteration can be separated into two different frequency areas: low frequency and higher frequency. ILC initially learns the low frequency area where the majority of error stays, but the remaining higher frequency errors grow as the number of iterations increases, which generates divergence in the intermediate trials until the higher frequencies can be learned. Thus the large overshoots that can occur in the learning transient depends on the initial error, which depend on the desired trajectory and time-domain feedback control scheme. For more detailed papers related to structure issues, see the following:

- Structure [315], [175], [332], [169], [424], [316].
- Equivalence of ILC to one-step minimum prediction control or feedback control [277], [433], [155], [314], [156], [153], [157], [154].
- Analysis in the point of passivity(dissipativity) [29], [24], [23], [31], [288], [22].
- Analysis in the point of positivity [171], [172], [139].

- Divergence observation [256].
- Steady-state oscillation condition and its utilization [222].
- Strongly positive system [10], [11].

2) *General (Update Rules)*: In this category, we include literature that discusses “ILC update rules” and their “performance comparisons.” Eventually, in ILC, the control force can be updated by

$$\begin{aligned}
u_{k+1}(t) = & \underbrace{\sum_{i=k}^{i=k-l} \sum_{j=0}^{j=n} \lambda_i(j) u_i(j) + \sum_{i=k}^{i=k-l} \sum_{j=0}^{j=n} \gamma_i(j) (y_d(j) - y_i(j))}_A \\
& + \underbrace{\sum_{j=0}^{j=t-1} \lambda_{k+1}(j) u_{k+1}(j) + \sum_{j=0}^{j=t-1} \gamma_{k+1}(j) (y_d(j) - y_{k+1}(j))}_B \\
& + \underbrace{\sum_{j=t}^{j=n} \lambda_{k+1}(j) u_{k+1}(j) + \sum_{j=t}^{j=n} \gamma_{k+1}(j) (y_d(j) - y_{k+1}(j))}_C
\end{aligned} \tag{27}$$

where  $A$  is for first-order and higher-order schemes,  $B$  is for current cycle update, and  $C$  is for anticipatory update. It is also natural to include D-type and I-type terms into (27) using the past error signals. When we consider the continuous case, these D-type and I-type can be also updated in a fractional way [54]. In [32], a Broyden-update-rule was used by solving the optimization problem

$$P_{k+1} = \arg \min_P \|P - P_k\|,$$

where  $P_k$  is the learning gain matrix for  $k$ -th iteration used in the update law  $u_{k+1} = u_k - P_k^{-1} e_k$ . In [118], [229], [120], there was a debate about a control law that ensures a zero output error for the whole desired trajectory after only one iteration trial. In these papers, they claimed that zero error can be assured only using the information about  $B$  and  $C$  matrices. Other debates have centered on the value of higher-order ILC. In [293], a first-order ILC algorithm and a second-order ILC algorithm were compared. From an industrial robot test, Norrlöf concluded that “it is not possible to say that a second-order ILC algorithm does better than a first-order algorithm.” However, Norrlöf also added that the second-order ILC scheme is very competitive when there is an uncertainty in the plant that makes the plant different between the iterations. Furthermore, he found that the second-order algorithm could smooth the behavior of the system by using the control and the error signal from more than one iteration. In [460], Xu, et al., compared previous-cycle learning (PCL), current-cycle learning (CCL), and synergetic previous- and current-cycle learning (PCCL). The conclusion was that PCCL has a better performance than PCL or CCL. Also, as remarked in the conclusion of [460], it was highlighted that ILC robustness can be enhanced by incorporating a current-cycle feedback. For various other ILC update rules, refer to the following categories:

- Update rules such as D-type ILC, P-type ILC, I-type ILC, PD-type ILC, and PID-type [464], [380], [57], [498], [381], [510], [174].
- Fractional [54].
- Using current cycle [338].
- Anticipatory [438].
- Update in Hilbert space [33], [32].
- Performance guaranteed ILC, convergence speed improvement, or performance improvement [466], [186], [478], [472], [473], [66], [118], [229], [120], [104], [423].
- Linearization [184].
- Automated/self tuning [258], [448], [262].
- Comparison of ILC update rules [460], [465], [293], [477].
- Discussion on convergence and/or robustness [303], [233], [307], [480].

3) *Typical ILC Problems*: In this category, we include ILC problems such as nonminimum phase, initial condition reset, higher-order approach, 2-D analysis, and frequency domain analysis. From Table 4.1 of [275], it is shown that these typical ILC problems had been popularly studied before 1997. But, we can observe that many publications are still devoted to these topics. It has been widely accepted that ILC can be very effective in controlling a nonminimum phase system because it uses noncausal filters (in traditional control theory, if a plant is nonminimum phase, perfect tracking cannot be achieved using causal operators). In [151], Ghosh and Paden designed a pseudo-inverse-based learning controller for the following nonlinear (could be nonminimum phase) affine system with disturbance:

$$\dot{x}_k(t) = f(x_k(t)) + g(x_k(t))u_k(t) + b(x_k(t))w_k(t), \quad x_k(0) = 0 \quad (28)$$

$$y_k(t) = h(x_k(t)) + v_k(t) \quad (29)$$

where  $w_k(t)$  includes both repetitive and random bounded disturbances. For solving this problem, Ghosh and Paden linearized the nonlinear system around the nominal plant using a first-order Taylor series and then used the pseudo-inverse of this linearized plant for the control force propagation. In [205], an input update law which depends on the number of nonminimum phase zeros was proposed using an iterative learning control scheme with advanced output data (ADILC). In [305], Ogoshi, et. al., used input-output linearization for the ILC system design of the nonlinear nonminimum phase system (28-29) (but without noise and disturbance). Sogo provided a stable inversion filter with a noncausal operation (see example 1 of [382]), and Verwoerd, et al., concluded that noncausal ILC outperforms causal ILC and ILC can be very effective in cases where the causality constraint imposed by the closed loop is the limiting factor [432].

Initial condition reset is one of the most critical assumptions of ILC. Many publications have been devoted to

relaxing this critical assumption. For example, Sun and Wang provided an analysis about initial reset for a nonlinear continuous ILC system [397] and for a nonlinear discrete ILC system [398], and suggested initial rectifying actions to improve the tracking performance. In [323], Park and Bien showed, for both linear and nonlinear systems, that  $\lim_{k \rightarrow \infty} y_k(t) = y_d(t) - \bar{e}(t)$ , where  $\bar{e}(t)$  is analytically determined from the initial reset error.

Higher-order ILC has been steadily studied for improving convergence speed and robustness [223]. In ILC, 2-D analysis has also been studied for a long time. The first 2-D approach in ILC field is [228], which was developed based on Kurek's early work [227]. Recently Fang and Chow [119] used 2-D theory for handling the initial reset problem of ILC. In fact, ILC system is a 2-D system in its nature. French, et al., [128] developed an adaptive iterative learning algorithm based on 2-D concept and Owens, et al., comprehensively explained the stability of higher-order ILC scheme, norm-optimal ILC, predictive norm-optimal ILC, and adaptive ILC based on 2-D concepts in [317].

In [346], a frequency domain-based learning update rule was introduced for the tracking control of a tooth-belt driven positioning table. For this purpose, a continuous periodic signal is approximated by discrete Fourier transform (DFT); then they use a feedback controller (PD control) and feedforward learning control for the control force calculation according to

$$u(t) = PD(t) + \hat{u}(t). \quad (30)$$

Then, transforming (30) into the discrete frequency domain, they proved convergence of a frequency-domain-based update rule (actually the proof was given in [416]). In [117], a frequency-domain-based stability analysis was given, by which the following two conditions need to be satisfied:

$$\begin{aligned} |1 - e^{jwT} \phi G(e^{jwT})| < 1 \quad \forall w \quad \text{For SISO} \\ \bar{\sigma}[1 - e^{jwT} \phi G(e^{jwT})] < 1 \quad \forall w \quad \text{For MIMO} \end{aligned} \quad (31)$$

where  $\phi$  is the learning gain (matrix). Since the inequality boundary of (31) is a unit circle centered at +1 in the Nyquist polar plot of  $z\phi G(z)$ , it was noted that the poor transient problem is due to the frequency range where the Nyquist plot is outside the unit circle. For eliminating this frequency range, it was concluded that a cutoff is needed and it was claimed that the cutoff is also necessary for good transient robustness. For a similar frequency-domain-based stability analysis, refer to [299]. Additional papers related to typical ILC problems include:

- Nonminimum phase and/or noncausal filter [151], [205], [150], [305], [207], [291], [382], [265], [383], [147], [226], [90], [208], [225], [432], [122], [123].
- Inverse model based or pseudo-inverse-based ILC [149], [148], [290].
- Initial setting (shift) [393], [323], [71], [325], [121], [398], [396], [397], [402], [405], [401], [501].

- Higher-order ILC [6], [70], [223], [479], [334], [300], [281].
- 2-D approach/analysis [119], [113], [276], [96], [114], [354], [141], [317], [142], [128], [161], [139], [112].
- Frequency domain analysis and/or synthesis based on frequency based filtering [384], [244], [346], [117], [299], [248], [298], [302], [51], [52], [339], [64].

4) *Robustness Against Uncertainty, Time-varying, and/or Stochastic Noise*: This category includes robustness problems such as disturbance rejection, stochastic affects,  $H_\infty$  approaches, etc. Arif, et al., [15] used the following update rule  $u_{k+1}(t) = u_k(t) + \Gamma_1 \dot{e}_k(t) + \Gamma_2 \dot{e}_{k+1}(t)$ , where  $\dot{e}_{k+1}(t)$  is the predicted error, to improve the ILC convergence speed for time-varying linear systems with unknown but bounded disturbances. In [425], time-periodic disturbances and non-structured disturbances were compensated using a simple recursive technique that does not use Lyapunov equation (refer to [470] for disturbance compensation using Lyapunov functions). For general ideas about robust ILC, refer to [273] for the linear case and see [440], [493], [74], [337], [483], [419], [421] for the nonlinear case. Other related papers include:

- Disturbance rejection with feedback control [83].
- Disturbance rejection with iteration-varying filter [297].
- Nonlinear stochastic systems with unknown dynamics and unknown noise statistics [49].
- Stochastic ILC [365], [363], [362], [48], [364] and with error prediction [15].
- Measurement noise [287], [296].
- $H_\infty$  approach [330].
- $\mu$ -Synthesis [105], [106].
- Model-based [21], [351].
- Based on backstepping ideas [425].
- Polytope uncertainty approach [250].

5) *Optimal, Quadratic, and/or Optimization*: Optimal ILC is considered as one of the main ILC theoretical areas and it has a well-established research history. Norm-optimal ILC is due to [137] as commented in [177]. Recently there have been several different quadratic cost function-based ILC algorithms. In this category, we consider these algorithms and other optimization-based methods. In [8], Amann, et al., proposed the so-called norm-optimal controller to determine a control force at the  $(k+1)^{th}$  iteration by minimizing the following cost function:

$$J_{k+1,N}(u_{k+1}) = \sum_{i=1}^N \lambda^{i-1} (\|e_{k+i}\|^2 + \|u_{k+i} - u_{k+i-1}\|^2), \quad (32)$$

where the weigh parameter  $\lambda$  determines the importance of more distant (future) errors and incremental inputs compared with the present ones. Note that (32) uses the next  $N$  trials' information (compare with the anticipatory algorithm [438]). In [8], an optimal control force is calculated as  $u_{k+1} = u_k + G^*(I + \lambda Q_{N-1})e_{k+1}$ , where

$e_{k+1}$  is recursively updated by  $e_{k+1} = [I + GG^*(I + \lambda Q_{N-1})]^{-1}e_k$  and  $Q_N$  is also recursively updated by  $Q_N = [I + GG^*(I + \lambda Q_{N-1})]^{-1}(I + \lambda Q_{N-1})$ . Gunnarsson and Norrlöf [164] interpreted the norm-optimal ILC in the frequency domain, and recently, in [177], norm-optimal ILC was used with a genetic algorithm for calculating the optimal learning gain for a class of nonlinear ILC problems. In [311], optimality-based adaptive ILC algorithms were developed. For nonlinear systems, Choi and Jang [89] used the steepest gradient method for minimizing a performance index function and in [221], singular value decomposition was used for analyzing a quadratic form-based optimal ILC algorithm. Other related references include:

- Optimal ILC [8], [170], [5], [177], [178], [179], [311], [360], [310], [427], [4], [180], [361], [182], [164], [181].
- Linear quadratic optimization-based method [309], [159].
- Quadratic cost function-based method [89], [221], [235], [129].
- Numerical optimization [267].

6) *Adaptive and/or Adaptive Approaches:* Adaptive control-based ILC is very popular and many theoretical works in ILC are related to Lyapunov functions and/or adaptive control concepts. In this category, we only include the literature which focuses on purely theoretical adaptive ILC. For robot manipulator control, adaptive learning control has been very popular. For example, in [391], an adaptive learning (A-L) control scheme was developed for robot manipulator tracking; in [272], Miyasato proposed a hybrid adaptive control scheme (enhanced by ILC), and in [94], Choi and Lee also provided a hybrid adaptive learning control scheme using both feedback control and feedforward control for robot manipulation. For non-robotic adaptive control-based ILC, in [125], French and Rogers consider the following system:

$$\begin{aligned}\dot{x}_i &= x_{i+1}, \quad i = 1, \dots, n-1 \\ \dot{x}_n &= \theta^T \phi(x) + u\end{aligned}$$

where  $\phi(x)$  is known and  $\theta \in \mathcal{R}^n$  are unknown parameters. If  $\hat{\theta}$  are the adaptively estimated parameters, it is shown that  $\hat{\theta}$  can be estimated such that  $(\theta - \hat{\theta})^T(\theta - \hat{\theta})$  is monotonically decreasing in a finite time horizon. Owens, et al., [318] used an adaptation learning gain update law and French, et al., [124] further provided a learning control scheme based on learning gain adaptation, using only the information of  $\text{sign}(BC)$ . In [76], a model reference adaptive control scheme for an affine nonlinear ILC system was developed based on output-feedback linearization and in [241] a discrete-time model reference adaptive learning control scheme was developed for a linear system. Other publications studying adaptive control-based ILC include:

- General works [391], [125], [502], [272], [77], [94], [50], [124], [318], [294], [47], [127].
- Model reference [76], [241].

- Model reference with basis functions [335], [446].

7) *Fuzzy or Neural Network ILC*: In the ILC literature, it has been shown that learning gains can be determined from neural network or fuzzy logic schemes [274]. Specific results include:

- Fuzzy ILC and fuzzy ILC for initial setting [75], [443], [82], [376], [509], [7], [340], [487].
- Feedforward controller (LFFC) using a dilated B-spline network [59], [431].
- Artificial neural networks for ILC and ILC applied to neural networks [496], [414], [80], [185], [198], [209], [95], [97], [215], [214], [253], [452], [486], [409], [444], [81], [377].

8) *ILC for Mechanical Nonlinearity Compensation*: Many ILC publications show that mechanical hard nonlinearities can be compensated successfully if they have some sort of periodicity in the time-, state-, or frequency-domain. The main idea of hard-nonlinearity compensation is to analyze stability in the iteration domain as done in [391]. That is, in the first iteration, we need to guarantee bounded-input bounded-output in an  $l_p$  norm topology. Then, from the second iteration and onward, asymptotic stability should be guaranteed as a function of iteration. Even though the main idea can be found in [481], the following publications can be referred to for stability analysis of specific hard-nonlinearity compensation strategies using ILC:

- ILC without a priori knowledge of control direction and with non-Lipschitz disturbance: [470], [491], [217].
- ILC with input saturation [467], [482].
- Input singularity [469], [490].
- Deadzone [494], [216], [359].
- Coulomb friction [108], [109], [146], [111].
- Using Smith predictor for time delay and disturbance system [197], [474].
- Delay [394], [324], [329].
- Backlash [201].

9) *ILC for Other Repetitive Systems and Control Schemes*: Though classical control theories have been utilized for ILC performance improvement, it is also possible to use ILC theory for the performance improvement of other control schemes. Using general idea of ILC, the performances of several other types of control strategies have been improved, including: repetitive control, PID, optimal control, neural network, etc., [143], [199], [43], [18], [313], [435], [91], [206]; and model-based predictive control [234], [239].

10) *Miscellaneous*: Papers that we cannot separate into the categories given above include:

- Different tracking control tasks [468].
- Slowly-varying trajectory and/or direct learning control (DLC) for nonrepeatable reference trajectory, or DLC for MIMO [13], [17], [484], [489], [488], [3].
- LMI ILC [138], [388], [144], [140], [355].

- Monotonic ILC [56], [278], [280], [284], [286], [327], [328].
- Hamiltonian control systems [135], [133], [134], [136], [132].
- MIMO linear time-varying system ILC [410].
- Observer-based ILC [419].
- Blended multiple model ILC [420].
- Composite energy function ILC [463], [488].
- Cascaded nonlinear system [349], [347].
- Nonlinear with constraint [53].
- Maximum phase nonlinear system [88].
- Unknown relative degree [392]; and arbitrary or higher relative degree [78], [403], [508], [20].
- Decentralized iterative learning control [450].
- Internal model based [422], [55], [58], [426], [492].
- Distributed parameter systems [348], [350].
- ILC with prescribed input-output subspace [165], [168]; with desired input in an appropriate finite dimensional input subspace [386], [387]; and with bounded input [110].
- Sampled data ILC [395], [399], [407], [406], [400], [401], [404].
- Experience/information database [14], [16], [13].
- Fourier series based learning controller [345].
- Learning variable structure control [471].
- With weighted local symmetrical integral feedback controller [63].
- Inter-sampling error [245].
- Model identification [255], [257].

Fig. 4 plots the number of papers related to theoretical developments in ILC. As seen in this figure, ILC theory has been advanced by being connected to existing control theories such as robust, adaptive, optimal and neural/fuzzy control. However, the ILC structure and update problems, which are investigated within ILC's own framework, dealing with ILC problems such as the non-minimum phase systems, the initial reset problem, the higher-order issue, 2-D analysis, and convergence/performance improvement, have been more widely studied. Fig. 4 reveals that lots of research are still devoted to ILC own theoretical and structural problems. It is also interesting to point out that while other control schemes have been used to help improve ILC, in the same way the ILC concept has been used for performance improvement of other control schemes.

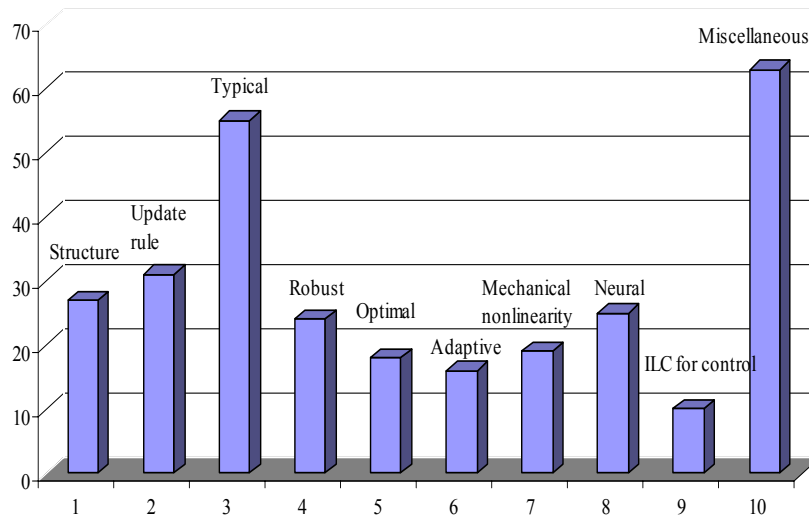


Fig. 4. Publication number of theory-focused ILC literature.

#### IV. DISCUSSIONS AND CONCLUSIONS

In this paper we have categorized and discussed the iterative learning control literature published between 1998 and 2004. Following a general introduction to ILC and a technical description of the methodology, selected results were reviewed and we then categorized the ILC literature within two broad divisions: application and theory.

From the categorization of application-related literature, we have found that ILC applications have been extended from robotics and process control to more specific semiconductor manufacturing and bio-engineering applications. However, applications remain dominated by manipulator-based robotics, rotary systems, and process control problems, which are basically time- or state-periodic in either the desired trajectory or the external disturbances. Although some of the publications have shown that ILC can be used in the areas of aerospace, non-robotic actuator control, bio-medical applications, visual tracking, artificial muscles, and other emerging engineering problems, successful industrial applications have not yet been reported in these areas.

From the survey of theory-focused literature, it is seen that ILC theory has been developed in two different areas: research on ILC's own features and research on ILC systems fused with other control theories. Most of the recent theoretical work has been related to performance improvement with various types of uncertainties and/or instabilities. However, although many recent theoretical achievements have provided beautiful mathematical formulations of ILC, much of the theoretical development remains far away from actual application considerations. From our observations, we would argue that it is more urgent to develop theoretical ILC works to support industrial ILC application, where the robust performance issues on the iteration domain may be more important.

As a disclaimer, we would note again that while we tried to include as many ILC publications as we could find, the literature search was restricted to the exact name of "iterative learning control." Thus, it is certain that we have missed many important ILC publications. Nonetheless, we believe that the survey work performed in this paper

can help the reader understand the overall trend of ILC in both applications and theory. We would finally repeat that research in ILC applications is still not so active as compared with purely theoretical works. Thus, it is our hope to see more publications that include successful ILC experimental results and/or industrial applications. In this respect, we hope that the next ILC survey to appear will find that more papers such as [259] will have been published.

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